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Electromagnetic precursors to the 2004 Mid Niigata Prefecture earthquake

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Abstract

This paper summarizes the electromagnetic precursory phenomena for the 2004 Mid Niigata Prefecture earthquake on October 23, 2004. Three different kinds of seismogenic perturbations have been observed; (1) lithospheric DC/ULF emissions, (2) atmospheric radio noise in the VHF band and (3) ionospheric disturbances. The DC/ULF emissions as observed at Nakatsugawa (in Gifu Prefecture) are detected on October 2–6, and the direction finding result has indicated the possible observed azimuth very close to the epicentral region. Then, we have observed the atmospheric radio noises in the VHF band on October 15–18, which are found to have the azimuth from Chofu very close to the epicentral zone. Finally, nearly at the same time (about one week before the earthquake) we have observed significant ionospheric perturbations on the subionospheric VLF/LF propagation characteristics by means of the shift in terminator time and enhancement in signal fluctuation for one particular path from the JJY (in Fukushima Prefecture) to Kochi. These perturbations not only in the lithosphere, but also in the atmosphere and ionosphere, are likely to be precursors to the 2004 Mid Niigata Prefecture earthquake.

Keywords: Electromagnetic precursors; ULF emission; VHF atmospheric emission; Ionospheric perturbations; The 2004 Niigata earthquake

1. Introduction

It has been reported that electromagnetic emissions are observed in a wide frequency range from DC, ULF to VHF in possible association with earthquakes (Hayakawa, 1999; Hayakawa and Molchanov, 2002). There seem to exist a few very promising candidates for short-term earthquake prediction including (1) ULF emissions and (2) ionospheric perturbations as detected by subionospheric VLF/LF propagation. The lower frequency range like ULF (ultra-low-frequency, frequency less than 10 Hz or so) is the most attractive because there have been convincing evidences on the precursory occurrence of ULF emissions before large earthquakes including Spitak, Loma Prieta, Guam etc. (e.g. Hayakawa and Hattori, 2004). Our recent studies have suggested that ULF emissions can be observed within the epicentral distance of ~100 km from an earthquake with magnitude 7, and of ~70–80 km for an earthquake with magnitude 6. However, Ohta et al. (2001) have successfully detected in Japan the ULF/ELF emissions which are associated with the Chi–Chi earthquake in Taiwan. Once they are exited into the atmosphere, they seem to be able to propagate over great distances as in the case studied by Ohta et al. (2001). The second candidate is the ionospheric perturbation as detected as subionospheric VLF/LF propagation anomaly (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998). Unlike the local measurement such as ULF emission measurement, this VLF/

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LF propagation method is an integrated measurement, so that it is much easier for us to accumulate the number of events than the local measurement. There have already been a lot of data suggesting the correlation between the ionospheric disturbances and earthquakes (Shvets et al., 2004; Rozhnoi et al., 2004). Though, of course, the epidemiological correlation between VLF anomalies and earthquakes is highly required and is in progress.

This paper deals with a particular recent earthquake event in Japan; we had a relatively large earthquake in October, 2004, which is named the 2004 Mid Niigata Prefecture earthquake. So, we want to present different electromagnetic phenomena in possible association with this particular earthquake. We discuss the lithospheric, atmospheric and ionospheric effects.

2. The 2004 Mid Niigata Prefecture earthquake, and the associated electromagnetic phenomena

First of all we describe this earthquake as follows. This earthquake took place at 17:56 LT on October 23, 2004, with magnitude of $M = 6.8$ (by Japan Meteorological Agency) and depth of 10 km. Its epicenter is located at the geographic coordinates (37.23°N, 138.78°E) and we had a few strong aftershocks.

We have been observing different kinds of electromagnetic phenomena (Hayakawa et al., 2004). In this paper will show the observational results on the following items: (1) lithospheric DC/ULF emissions, (2) atmospheric effect in the form of VHF natural noises and (3) ionospheric disturbances as detected by subionospheric VLF/LF propagation. In the following we will describe each item one by one.

3. DC/ULF lithospheric emission as observed at Nakatsugawa

We have been observing ELF emissions at Nakatsugawa in the Gifu prefecture since 1999, and the details of the ULF/ELF observation system has already been described in Ohta et al. (2001). Essential points at this observing station are repeated here. We have three orthogonal induction coils (1.2 m permalloy) as magnetic sensors and we observe three magnetic field components (B_x, B_y and B_z; x, y are the horizontal axes, and z is the vertical axis). The signals from magnetic field components are amplified by means of preamplifiers (gain = 66 dB) with the low pass filter (with cutoff of 30 Hz). Then the signals (waveforms) are converted by means of an A/D converter with sampling frequency of 100 Hz, and they are stored on a hard disc every six hours. The daily dataset consists of four files; file 0: 00 h to 6 h LT, file 1: 06 h to 12 h, file 2: 12 h to 18 h, and file 3: 18 h to 24 h.

Signal analysis is based on the FFT (fast Fourier transform) with data length of 1024, so that the temporal resolution is about 10 s and the corresponding frequency resolution is about 0.1 Hz. We can measure the amplitude ratio and phase difference among the three components in the frequency range from 0 Hz to 50 Hz.

The top panel of Fig. 1 shows the temporal evolution of the magnetic field intensity (horizontal B_y component: sensitive to the waves propagating in the NS meridian plane) at a particular frequency of 0.1 Hz (to be exact, this frequency means the frequency from DC to 0.1 Hz). The intensity is averaged over one file with duration of six hours, and the period is from the middle of September to the end of October, because the 2004 Mid-Niigata Prefecture earthquake occurred on October 23. The bottom panel of Fig. 1 refers to the corresponding variation at the higher frequency of 1.0 Hz.

When we look at the temporal evolutions at different frequencies in Fig. 1, we notice a noticeable and significant difference between the two (one below 0.1 Hz and one at 1 Hz). For higher frequencies such as 1.0 Hz, 3.0 Hz and 5.0 Hz (the latter two are not shown in the figure), the temporal evolution is found to exhibit a very regular diurnal pattern: the noise for the file 0 (00 h to 06 h LT) is extremely at low level, it increases to the maximum due to the human (or industrial) activity for the file 1 (06 h to 12 h), it shows a slight decrease due to the lunch-time effect for the file 2 (12 h to 18 h), and it increases again for the file 3 (18 h to 24 h). In the top panel of Fig. 1, the horizontal full lines indicate the mean value for the month of October, and the horizontal dotted line refers to the level of the mean value +3 dB. It is seen from the top panel that there

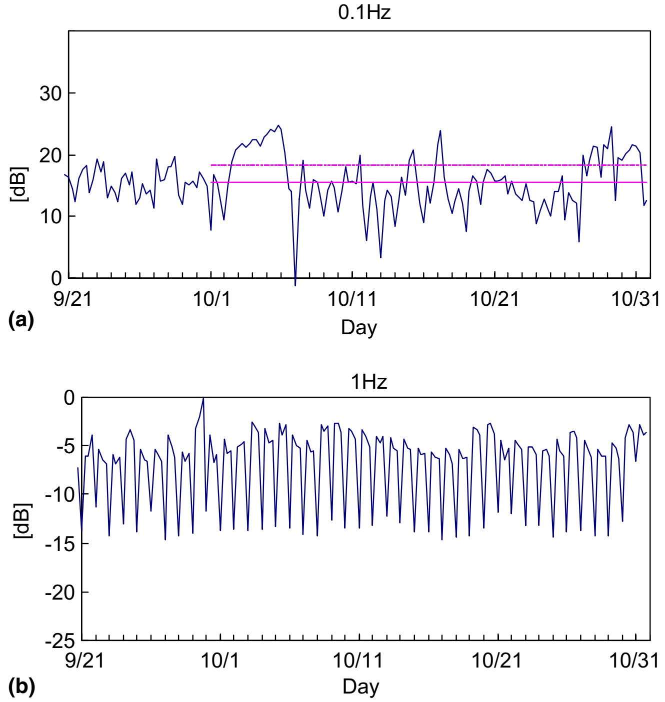

Fig. 1. Temporal evolutions of the magnetic field component B_y at different frequencies; (a) 0.1 Hz (top panel), and (b) 1.0 Hz (bottom panel). The period is from September 21 to October 31, 2004. The horizontal full line in the top panel is the mean value for October, and the horizontal dotted line, the level of (mean +3 dB).

are only very limited time intervals in which the noise level keeps the high level exceeding the level of mean +3 dB; that is, the period from October 2, file 1 to October 6, file 0 and another is on October 30 and 31. On the latter two days we can notice the more enhanced effect of atmospherics at higher frequencies over the lower frequency background. So, the enhanced level on October 30 and 31 in the top panel of Fig. 1 is apparently due to the effect of atmospheric noise. Then, we make some more detailed analysis for the enhancement of noise level during the period of October 2–6.

We perform the direction finding for the noises during the period when the noise intensity exceeds +3 dB above the average. The direction finding is the conventional goniometer by using only the two horizontal magnetic components (Hayakawa, 1995; Ohta et al., 2001). Of course, the system of direction finding at lower frequencies of our concern is not well established. When we observed seismogenic ELF emissions at Nakatsugawa, which are possibly associated with the Chi–Chi earthquake in Taiwan, the polarization was nearly linearly polarized so that we could expect that the waves were quasi-TEM mode (Ohta et al., 2001), which enabled us to perform the successful use of a goniometer. This is the reason why we use the same goniometer concept here.

The determination of azimuthal direction is carried out for intense DC/ULF emissions by means of the gonimometer principal. Table 1 is the summary of the direction finding results (the average value for each file (or for 6 h)), together with the average intensity. The azimuth is indicated northward from the geographic East direction (as estimated from $\tan^{-1}(B_y/B_x)$). The average azimuth is about 55° northward from the east, which means that the noise during the period of October 2–6 is arriving from 55° north of the east. These noise enhancements are found to exhibit no diurnal patterns as in the bottom panel of Fig. 1 for higher frequencies, which may be suggestive that these noises are not artificial (due to human activity). Fig. 2 illustrates the average azimuth in Table 1, and we can conclude that this azimuth is very close to the epicenters of the 2004 Mid Niigata Prefecture earthquakes. So that the noises on October 2–6 are highly likely to be associated with the Niigata earthquakes.

Here we have to check the geomagnetic activity and local lightning activity during the period of Fig. 1. Fig. 3 illustrates the temporal evolution of $\sum K_p$ (daily sum of K_p index) during the period. Because the maximum $\sum K_p$ is only 34 during the period of Fig. 1, this is an indication that this period is generally geomagnetically quiet. And the

Table 1
Summary of the intensity and azimuthal angle estimated at the frequency below 0.1 Hz

Day	File number	Intensity (dB)	Azimuth angle (°)
October 2	2	18.9	52
October 2	3	20.6	51
October 3	0	21.2	50
October 3	1	21.7	52
October 3	2	21.2	51
October 3	3	21.7	53
October 4	0	22.4	61
October 4	1	22.2	59
October 4	2	21.3	51
October 4	3	22.9	55
October 5	0	23.3	54
October 5	1	24.1	55
October 5	2	23.7	52
October 5	3	24.8	53
October 6	0	24.0	59
October 6	1	20.3	66

The average intensity and average azimuthal angle are indicated for each file of 6 h.

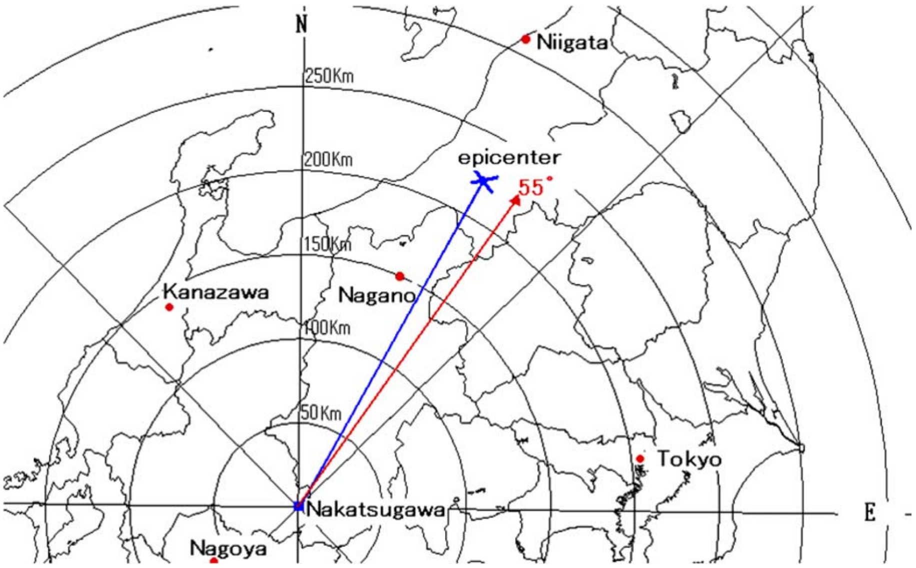

Fig. 2. Relative location of our observing station at Nakatsugawa (Gifu Prefecture) and the epicenter of the main shock of the 2004 Mid Niigata Prefecture earthquake. The goniometric direction finding result from Nakatsugawa is given by an arrow (55°).

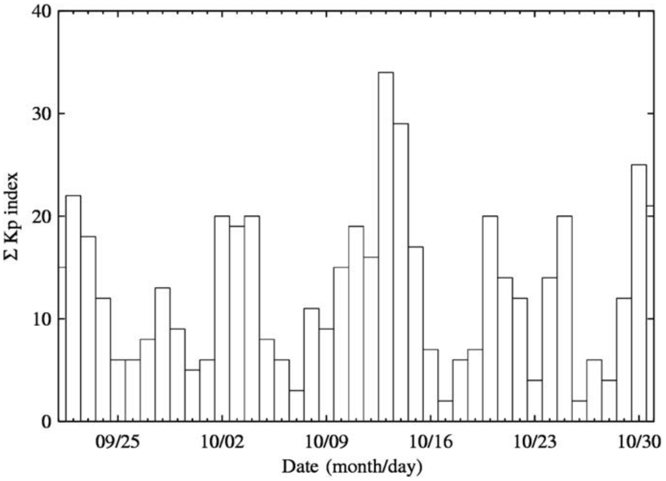

Fig. 3. Temporal evolution of $\sum K_p$ index during the relevant period.

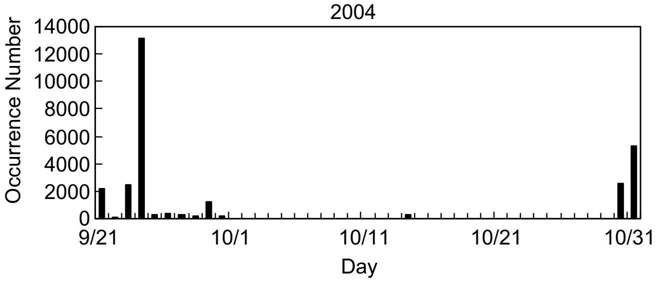

Fig. 4. Temporal evolution of the occurrence number of lightning discharges around our ELF station of Nakatsugawa.

period of October 2–6 is found to be in the extremely low geomagnetic activity. Next, Fig. 4 illustrates the temporal evolution of the occurrence number of total lightning discharges on a current day observed within 150 km around our observation station of Nakatsugawa. Fig. 4 shows the local enhancement of lightning discharges on October 30 and 31 and September 24. A comparison of this with the top panel of Fig. 1 indicates that an enhancement on October 30 and 31 may be related with local lightning, but no effect is seen in the top panel of Fig. 1 on September 24. The period of the most enhanced wave activity on October 2–6 in Fig. 1 is found to be completely free from the local lightning activity in Fig. 4. So that, the enhancement on October 2–6 is likely to be a precursor to the earthquake.

4. Ionospheric perturbation and atmospheric noise

As is shown in Hayakawa et al. (2004), we have a Japanese VLF/LF network consisting of seven observing stations in Japan, and at each station we receive the subionospheric signals from four VLF transmitters (NWC (Australia), NPM (Hawaii), NLK (USA) and JJI (Ebino, Japan)) and one LF Japanese transmitter (JJY in Fukushima Prefecture). The observed data (amplitude and phase) on the VLF/LF subionospheric signals are transmitted to our master station of Chofu (University of Electro-Communications) every day. The observation on the seismo-ionospheric perturbations is made with the sampling frequency of 120 s (2 min), which is sufficient to take into account the slow changes associated with the earthquakes. A combination of seven observing stations with the receiving VLF/LF transmitters provides us with the ionospheric information over the total of over 30 propagation paths.

A lot of papers have been published on the ionospheric perturbation associated with earthquakes by means of subionospheric VLF/LF propagation (i.e., Hayakawa et al., 1996; Molchanov et al., 1998; Molchanov and Hayakawa, 1998). Two methods of analysis have been proposed to identify the seismo-ionospheric perturbations. The first method is the so-called "terminator time" method, in which we measure the times (around sunset and sunrise) when the diurnal variation of amplitude (and/or phase) of the VLF signal exhibits a minimum (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998). These authors have shown that the terminator times (sunrise and sunset) exhibit anomalous shifts in possible association with earthquakes. This shift in the terminator time is theoretically explained by means of the seismo-ionospheric perturbation by using the full-wave computations (Soloviev and Hayakawa, 2002; Soloviev et al., 2004; Rozhnoi et al., 2004). The second method is based on the analysis of nighttime fluctuation spectra in the amplitude (and/or phase) (Molchanov et al., 2001; Miyaki et al., 2002; Shvets et al., 2002, 2004). This is based on the hypothesis of the important role of the atmospheric gravity wave (AGW) because there have been reports on the close correlation between the fluctuation spectra in the frequency range of AGW and the earthquakes (Molchanov et al., 2001; Miyaki et al., 2002; Shvets et al., 2002, 2004).

We present the results only for one particular path (Transmitter: JJY (40 kHz, Fukushima Prefecture) and receiving station: Kochi (Kochi University)), because the great-circle path for this propagation path is very close to the epicenter of Mid-Niigata Prefecture earthquake as shown in Fig. 5. The area enclosed by the curve in Fig. 5 is characterized by the 5th Fresnel zone of the great-circle path, which indicates that this is a sensitive area for this propagation path. Fig. 6(a) illustrates the analysis results on the shift in the terminator time for the propagation path of JJY to Kochi. This propagation path is nearly in the east–west direction, so that this path is very suitable for studying the behavior of the terminator time (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Maekawa and Hayakawa, 2006). Evening terminator time was difficult to read, so that the morning terminator time has only been used in plotting Fig. 6(a). The terminator times observed during one whole year can be well fitted by a combination of an annual variation and a semi-annual variation. It is clearly seen that the terminator time exhibits a significant shift from the mean value (indicated as zero in the figure) just around the times of the earthquakes. The

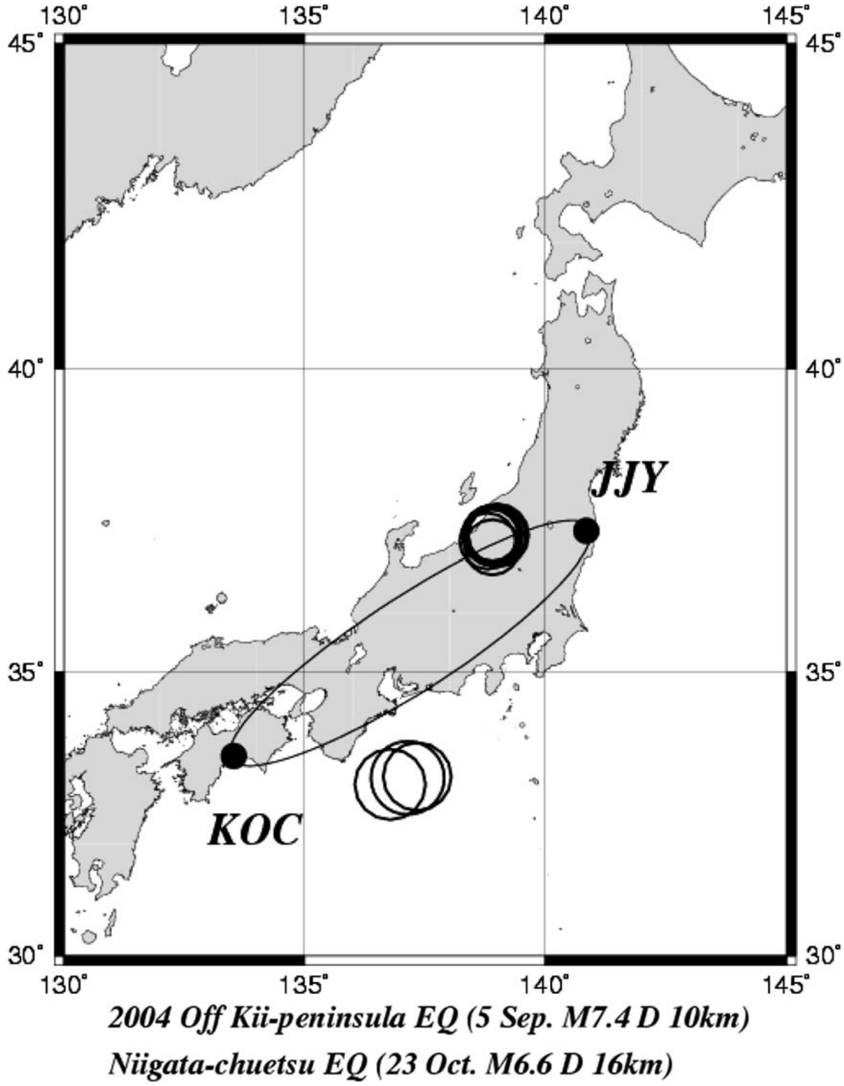

Fig. 5. Locations of epicenters for the two large earthquakes (off Kii peninsula earthquake, Mid-Niigata Prefecture earthquake). Also, we have plotted the fifth Fresnel zone of the propagation path between JJY and our Kochi (KOC) receiving station.

difference between the current terminator time value and the above fitted curve, is subject to the analysis. The standard deviation is based on the running averaging over ±15 days. A few peaks exceeding 2σ (σ is standard deviation) are found on October 11 and October 20 before the earthquake main shock, and also a few peaks after the main shock. The peaks before the main shock are highly likely to be a precursor to the main shock.

Fig. 6(b) illustrates the sequential plot of nighttime amplitude fluctuation day by day, which seems to indicate that there is an enhanced fluctuation just around the earthquake times. By applying the FFT analysis only to the nighttime (LT = 19–05 h), we first estimate the fluctuation power spectrum density in the frequency range of AGW (10 min to a few hours) and we integrate it over the fluctuation frequency range from 10 min to 3 h (one datum for one day). The standard deviation in the figure is based on the averaging over ±15 days. The daily variation of this quantity is plotted in Fig. 7 in order to understand the daily diurnal patterns of the amplitude and we are able to find the nighttime fluctuation very easily. The figure indicates the clear appearance of a significant peak in the fluctuation about one week before the earthquakes, which may be a precursory effect. This seems to be very consistent with the above results obtained by the terminator time method.

Our previous event studies (both on the terminator time shift and fluctuation analysis) based on many events (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Shvets et al., 2004) have indicated that probability of having the perturbation in the lower ionosphere is about 80% for the earthquakes that are close to the great-circle path, with magnitude greater than 6.0 and with shallow depth. Our latest statistical studies by Shvets et al. (2002) and Rozhnoi et al. (2004) have suggested that the seismic effect can be detected when the earthquake magnitude is, at least, greater than 5.5. Taking into account these case- and statistical-studies, the results presented in this paper on the terminator time shift and fluctuation spectra are

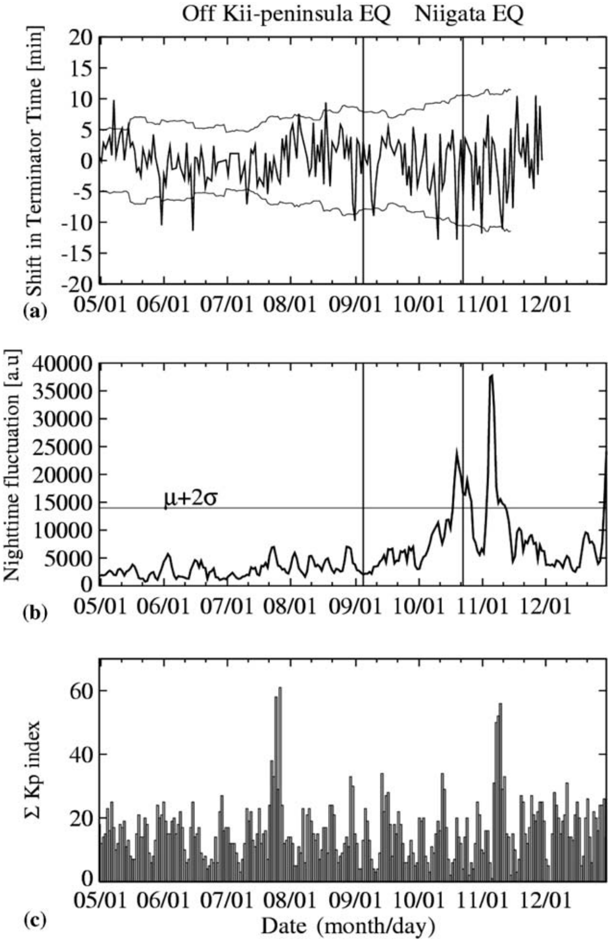

Fig. 6. (a) Temporal evolution of shift in the terminator time (morning) for the path from JJY to Kochi. Zero line means the mean value, and the current value on a day is the running average over ±3 days. 2σ (σ: standard deviation (averaging over ±3 days)) is also plotted for the sake of comparison. (b) Temporal evolution of the spectral power density of the fluctuation in the frequency of AGW (from the period of 10 min to 3 h). (c) $\sum K_p$ index.

likely to be supported by our above-mentioned works. The present results are indicative of the presence of some precursory ionospheric perturbations in the vicinity of the great-circle path from the JJY to Kochi, suggesting the occurrence of a future shallow earthquake with magnitude greater than 6.0. However, the location of the future earthquake is quite unknown from this study.

Then, we go to the atmospheric noise in the VHF band. By using the receiving system for over-horizon VHF signal by Fukumoto et al. (2001), we have been observing at Chofu (UEC) the reception of over-horizon VHF signal from the FM Sendai transmitter (frequency, 77.1 MHz). Fukumoto et al. (2001) have shown that the VHF signal from the FM Sendai which cannot be received normally at Chofu, is often received even at Chofu as a precursor to any earthquake (about one week before the earthquake) taking place close to the great-circle path. Fig. 8 illustrates the result on VHF signal at Chofu in October 2004. The antenna system used in Chofu, can be found in Fukumoto et al. (2001). Our antenna system enables us to estimate both the azimuthal and incident angle of the incoming wave. Only the nighttime data (LT = 0–6 h) are used because the University of Air is operating in Tokyo during daytime at the same frequency. The polarization is horizontal. The outputs from the vertical antenna are found to be extremely small, so that we show only the outputs from the horizontal antennas in Fig. 8. The orange color refers to the signal output from the horizontal antenna directed eastward of the great-circle path (+30°), while the black, the signal output from the horizontal antenna directed west of the path (−30°). First we pay our attention to the signal outputs occurring on 8, 10 and 12 October, which exhibit a little higher output for the direction of +30° than that for −30°. The aural monitoring tells us that these VHF signals are exactly attributed to the FM Sendai, which means that these are the reception of over-horizon

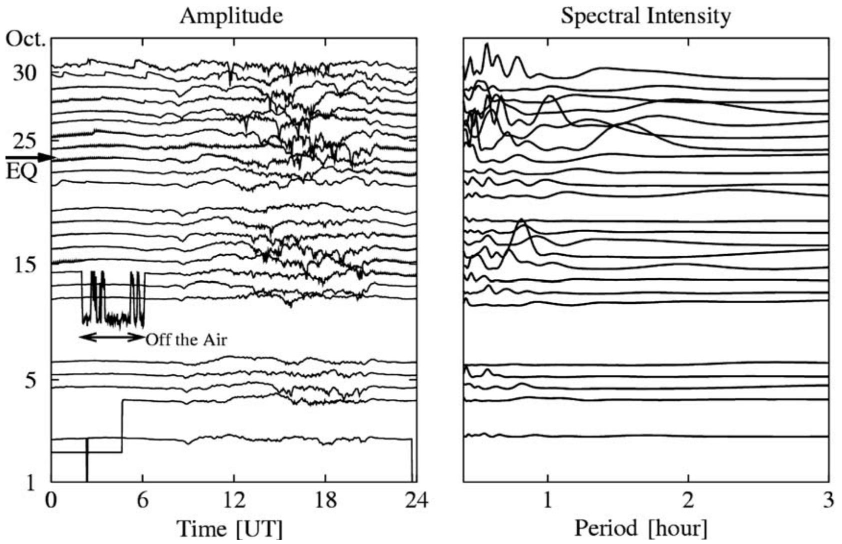

Fig. 7. Sequential plot of diurnal variation of the LF amplitude during local nighttime, LT = UT + 9 h. You can identify the enhancement of fluctuation before the Niigata earthquake.

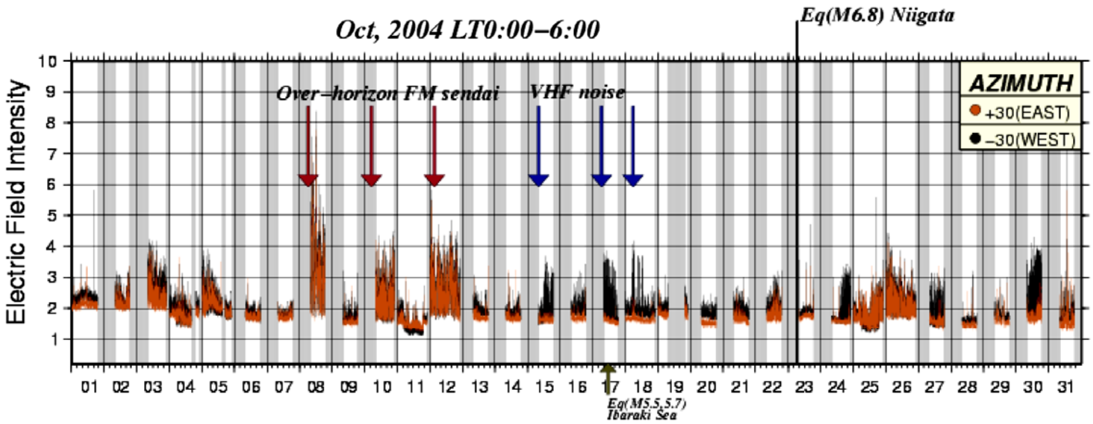

Fig. 8. The temporal evolution of over-horizon VHF signals from the FM Sendai station. Only nighttime (LT = 0 h–6 h) data are available because another VHF transmitter is in operation at the same frequency in Tokyo. The receiving station is Chofu (University of Electro-Communications). The outputs from two Yagi antennas (both horizontal) are shown; one directed west of the Sendai–Chofu path (azimuth = −30°, in black) and another, east of the path (azimuth = +30°, in orange).

VHF signal in possible association with earthquakes, as already found by Fukumoto et al. (2001). In correspondence with the lead time of a few days to about a week found by Fukumoto et al. (2001), the two earthquakes with magnitudes of 5.5 and 5.7 did actually occur on the day of 17 October and their epicenters were in the off Ibaraki Prefecture. The epicenter places seem to be consistent with the direction finding.

Strong noise bursts which have never been observed before during our previous observational period of three years, are first observed at Chofu on a few days from 15 to 18 October. The aural monitoring of the received signals indicates that these signals are not due to the over-horizon FM Sendai, but are completely natural noise in the VHF band. There have been so far very few reports on the seismogenic VHF noise; Warwick et al. (1982) observed VHF noise associated with the Chili earthquake and Maeda and Tokimasa (1996) have observed VHF noise for the Kobe earthquake. A comparison of the signal outputs from the antennas directed east and west of the path indicates that the signal from the west (−30°) is significantly more enhanced than that for the azimuth (+30°). The quantitative estimation on the arriving azimuth for the VHF noise bursts (with taking into account the antenna directivity (Fukumoto et al., 2001)) provides us with the azimuth of the incoming VHF noise as shown in Fig. 9, which is directed toward the epicenters of Mid Niigata prefecture earthquakes. You may feel that this direction is slightly away from the epicentral regions. But, the area of VHF noise emissions is considerably scattered or broad when taking into account the large magnitude of the earthquake. About one week later, Mid Niigata Prefecture earthquake did take place. Hence, it is highly likely that the VHF noise bursts on a few days from 15 to 18 October is a precursory to Mid Niigata prefecture earthquake on 23 October. Fig. 9 suggests a few more similar noise bursts on several days, and we have to check the association of these noises with the subsequent large aftershocks.

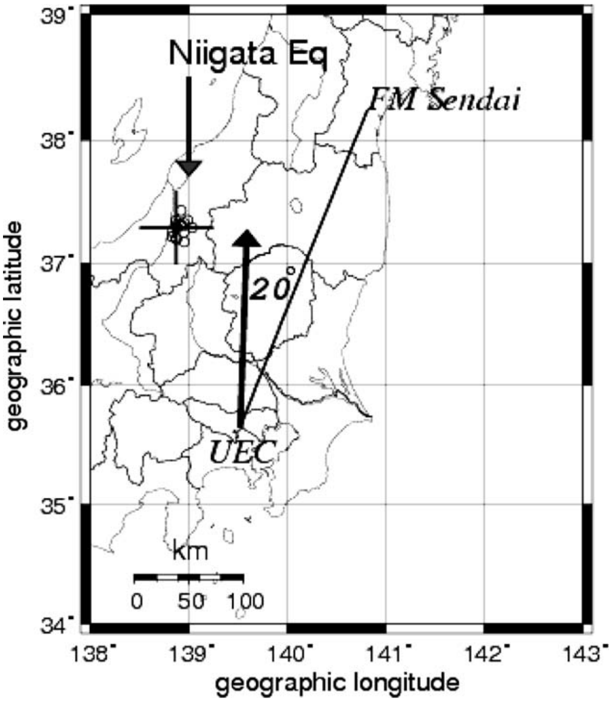

Fig. 9. The relative location of our observation of over-horizon VHF signal. The transmitter is FM Sendai, and the receiving station is Chofu. The direction finding result of the anomalous VHF noise bursts is given by an arrow (about 20° west of the path), directing to the future Niigata earthquake.

5. Conclusion and discussion

As you can see from the previous sections, it seems that this Niigata earthquake is very rich in electromagnetic phenomena or effects; lithospheric DC/ULF emissions, atmospheric noise in the VHF band and ionospheric perturbations.

First, we discuss the DC/ULF seismogenic emissions. We paid our particular attention to the two time periods when the noise level below 0.1 Hz is enhanced; October 2–6 and October 30 and 31. The noises on the two days of October 30 and 31 are found to be the enhanced occurrence of atmospherics. While, the former, elongated period of October 2–6 is found to be completely different from the event on October 30 and 31. The most important finding is that the noises below 0.1 Hz are linearly polarized and they are coming to the observatory from 55° north of the east direction. This azimuth is very close to the area of epicenters of the 2004 Mid Niigata Prefecture earthquakes. We may conclude that these noises are highly likely to be related to the earthquakes or a precursor to the earthquakes. The lead time is of order of 17–21 days (or two to three weeks), which seems to be consistent with the previous works (Hayakawa and Hattori, 2004).

A few things should be commented here. This is just the preliminary analysis result, but the most serious point is that the seismogenic ULF emissions have propagated from over about 230 km from the epicenters. The former experimental facts for ULF emissions have indicated that the ULF emission is observable with the epicentral distance of about 100 km for the magnitude 7 (Hayakawa and Hattori, 2004). This discrepancy might be related with the generation mechanism of seismogenic ULF emissions. There have been proposed a few mechanisms including the microfracturing mechanism by Molchanov and Hayakawa (1995) and Kawate et al. (1998) used Biot–Savart's law and full-wave computations to estimate the magnetic field intensity expected on the ground by assuming the current source in the hypocenter. When the seismogenic emissions are generated in the Earth's crust, the empirical law by Hayakawa and Hattori (2004) will be applied on the detection criterion between the magnitude and epicentral distance (i.e., about 100 km for $M = 7.0$). However, when the depth of an earthquake is very small (i.e., less than 10 km or so), the seismogenic ULF emissions might be generated near the Earth's surface or in the atmosphere. In this case they seem to be able to propagate in the Earth–ionosphere waveguide over great distances as the quasi-TEM mode of propagation. A typical example of this case is the Chi–Chi case by Ohta et al. (2001). The present case will be the second case.

We have to suggest the future works to do. In this paper the important frequency of seismogenic emission is at ULF, below the frequency of 0.1 Hz. But, we have to enhance the frequency resolution in order to find at which frequency the DC/ULF emission is dominating. The next problem is the use of any other ULF/LELF stations. We have a few other stations in Japan, e.g., Izu peninsula station (Hayakawa and Hattori, 2004) and Moshiri (Hokkaido) station (Ando et al., 2005). We will perform a similar analysis at one of those stations, and will perform the direction finding there to locate the source by means of triangulation.

We now discuss the atmospheric and ionospheric effects in possible association with the Niigata earthquake. We have already got a lot of information on seismo-ionospheric perturbations (Molchanov and Hayakawa, 1998) since our clear evidence for the Kobe earthquake (Hayakawa et al., 1996). A significant fluctuation in the nighttime amplitude variation is observed about one week before the earthquake, and this lead time is typical for the seismo-ionospheric perturbations (as already found from Molchanov and Hayakawa (1998)). In Fig. 6, we have plotted the 5th Fresnel zone of the propagation path from the JJY to Kochi (KOC), which seems to be sensitive to any large earthquakes within this Fresnel zone. A single path is unable to locate the region of ionospheric perturbation, but it will be possible to locate the perturbation by means of the combined use of different propagation paths. (This is under study, and it takes some more time to finish.)

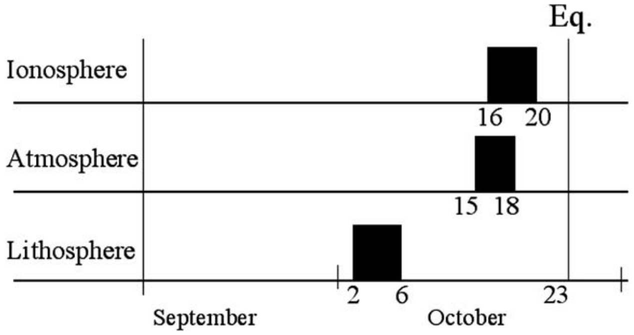

Fig. 10. Schematic summary on the temporal variation of different perturbation phenomena.

The last is the seismogenic atmospheric noise in the VHF band. We stress that this is the first time that we have received such a strong VHF natural noise since our observation commencement of over-horizon VHF transmitter signal. Fortunately our direction finding system has enabled us to locate the source, and we have found that the VHF noise source is lying very close to the epicenter of the earthquake.

Fig. 10 is the summary of the temporal evolution of seismic effects taking place in the different regions (lithosphere, atmosphere and ionosphere) for this Niigata earthquake. As is seen from the figure, the lithospheric effect in the DC/ULF range occurs first about two to three weeks before the earthquake and its duration is of the order of a few days. Then, atmospheric effect is found to follow; it occurs about one week before the earthquake. Finally, we have observed the perturbations in the ionosphere less than one week before the earthquake. We will study, in future, three temporal evaluations in the light of lithosphere–atmosphere–ionosphere coupling concept.

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References

Ando, Y., Maltsev, P., Sukhynyuk, A., Goto, T., Yamauchi, T., Hobara, Y., Sekiguchi, M., Ikegami, Y., Sera, M., Korepanov, V., Hayakawa, M., 2005. New ELF observation system at Moshiri, Japan and assessment of acquired data. J. Atmos. Electr. 25 (1), 29–39.

Fukumoto, Y., Hayakawa, M., Yasuda, H., 2001. Investigation of over-horizon VHF radio signals associated with earthquakes. Natural Hazards Earth Syst. Sci. 1, 107–112.

Hayakawa, M., 1995. Whistlers. In: Volland, H. (Ed.), Handbook of Atmospheric Electrodynamics. CRC Press, Boca Raton (Chapter 7).

Hayakawa, M. (Ed.), 1999. Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. Terra Sci. Pub. Co., Tokyo, p. 996.

Hayakawa, M., Hattori, K., 2004. Ultra-low-frequency electromagnetic emissions associated with earthquakes. Inst. Electr. Eng. Jpn., Trans. Fundamentals Mater. 124 (12), 1101–1108.

Hayakawa, M., Molchanov, O.A. (Eds.), 2002. Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. TERRAPUB, Tokyo, p. 477.

Hayakawa, M., Molchanov, O.A.NASDA/UEC team, 2004. Achievements of NASDA's Earthquake Remote Sensing Frontier Project. Terr. Atmos. Ocean. Sci. 15, 311–328.

Hayakawa, M., Molchanov, O.A., Ondoh, T., Kawai, E., 1996. The precursory signature effect of the Kobe earthquake on VLF subionospheric signals. J. Comm. Res. Lab. Tokyo 43, 169–180.

Kawate, R., Molchanov, O.A., Hayakawa, M., 1998. Ultra-low-frequency magnetic fields during the Guam earthquake of 8 August 1993 and their interpretation. Phys. Earth Planet Inter. 105, 239–248.

Maeda, K., Tokimasa, N., 1996. Decametric radiation at the time of the Hyogo-ken Nambu earthquake near Kobe in 1995. Geophys. Res. Lett. 23, 2433–2436.

Maekawa, S., Hayakawa, M., 2006. Dependence of characteristics of VLF/LF terminator times on the propagation direction: Statistical study, Inst. Electr. Eng. Japan, Special Issue on Seismo Electromagnetics 126, 220–226.

Miyaki, K., Hayakawa, M., Molchanov, O.A., 2002. The role of gravity waves in the Lithosphere–Ionosphere coupling, as revealed from the subionospheric LF propagation data. In: Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. TERRAPUB, Tokyo, pp. 229–232.

Molchanov, O.A., Hayakawa, M., 1995. Generation of ULF electromagnetic emissions by microfracturing. Geophys. Res. Lett. 22, 3091–3094.

Molchanov, O.A., Hayakawa, M., 1998. Subionospheric VLF signal perturbations possibly related to earthquakes. J. Geophys. Res. 103, 17489–17504.

Molchanov, O.A., Hayakawa, M., Ondoh, T., Kawai, E., 1998. Precursory effects in the subionospheric VLF signals for the Kobe earthquake. Phys. Earth Planet Inter. 105, 239–248.

Molchanov, O.A., Hayakawa, M., Miyaki, K., 2001. VLF/LF sounding of the lower ionosphere to study the role of atmospheric oscillations in the lithosphere–ionosphere coupling. Adv. Polar Upper Atmos. Res. 15, 146–158.

Ohta, K., Umeda, K., Watanabe, N., Hayakawa, M., 2001. ULF/ELF emissions observed in Japan, possibly associated with the Chi–Chi earthquake in Taiwan. Natural Hazards Earth Syst. Sci. 1, 37–42.

Rozhnoi, R., Solovieva, M.S., Molchanov, O.A., Hayakawa, M., 2004. Middle latitude LF (40 kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions. Phys. Chem. Earth 29, 589–598.

Shvets, A.V., Hayakawa, M., Molchanov, O.A., 2002. Subionospheric VLF monitoring for earthquake-related ionospheric perturbations. J. Atmos. Electr. 22, 87–99.

Shvets, A.V., Hayakawa, M., Molchanov, O.A., Ando, Y., 2004. A study of ionospheric response to regional seismic activity by VLF radio sounding. Phys. Chem. Earth 29, 267–287.

Soloviev, O.V., Hayakawa, M., 2002. Three-dimensional subionospheric VLF field diffraction by a truncated highly conducting cylinder and its application to the Trimpi effect problem. Radio Sci. 37 (5), 1079 doi:10.1029/2001RS002499.

Soloviev, O.V., Hayakawa, M., Ivanov, V.I., Molchanov, O.A., 2004. Seismo-electromagnetic phenomenon in the atmosphere in terms of 3D subionospheric radio wave propagation problem. Phys. Chem. Earth 29, 639–647.

Warwick, J.W., Stoker, C., Meyer, T.R., 1982. Radio emission associated with rock fracture: Possible application to the great Chilean earthquake of May 22, 1960. J. Geophys. Res. 87, 2851–2859.